

PLUTO EXPRESS SCIENCECRAFT SYSTEM DESIGN

H.W. Price, J.B. Carraway, S.E. Matousek, R.L. Staehle, R.J. Terrile, E.J. Wyatt
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

ABSTRACT

A number of mission system architectures have been studied for a Pluto flyby mission, with the goal of achieving the most cost effective means of meeting a well defined set of science and technology objectives. The current Pluto Express approach at NASA JPL incorporates emerging new technologies to reduce cost, mass, power, and volume, without sacrificing performance, science, or operations capability. The design has evolved through a number of option studies involving an extensive trade space which includes alternate power sources and various propulsion and trajectory options. The results of this trade study have been coupled with a new development implementation approach to create a highly integrated concurrently engineered mission system called a "sciencecraft." The current approach results in a Sciencecraft Module with dry mass of less than 100 kg, power consumption of less than 100 watts, and functional simplicity to achieve high reliability, operability, and a low total mission cost.

INTRODUCTION

Since 1992, a pre-project effort has been underway at NASA JPL to develop a Pluto flyby mission system design which would push the state of the art in low mass advanced technologies. The goal is now to enable an exciting science mission with a flight time of on the order of ten years using only a medium sized launch vehicle in order to keep down launch costs. Constant pressure to keep lowering total mission costs has led to a continuing evolution of the flight system, mission, and operations architecture. An integrated implementation team, a co-located design center with concurrent engineering tools, and a development testbed for the flight system and ground systems are key elements being used by the Pluto Express Team to lower the development and operations costs of both hardware and software.

The current plan is to have two launches to Pluto, each carrying one flight system and possibly, attached probes. The probes would be released at Pluto and Charon, or perhaps even at Io on the way out to Pluto. High resolution visible and IR images, UV spectra, and uplink radio science phase shift data will be taken during the high speed Pluto/Charon encounters and stored on board for later transmission to Earth over several weeks. Then the flight systems will be targeted to encounter one or more Kuiper Disk objects as they continue their journeys out into interstellar space.

New breakthroughs in advanced technology spacecraft components, electronics, and software allow for the development of a sophisticated, fully redundant outer planet explorer with a dry mass of under 100 kg, not including the Propulsion Module. Advanced technology development efforts funded by NASA in the last few years have brought many of these key new technologies to near flight readiness. Some of the most important developments include a miniaturized high efficiency telecommunications subsystem, a radiation hardened RISC multichip module Advanced Flight Computer (AFC), integrated Multi-Chip Module (MCM) microelectronics, low mass and low power highly integrated multispectral science instruments, autonomous spacecraft operations software, a new generation of monolithic ultralight composite structures, advanced radioisotope electric conversion technology, and Beacon Cruise mission operations that utilize on-board self-monitoring and self-commanding. Many of these technologies are being pathfinded by NASA's New Millennium Program (NMP).

Other enabling technologies result from breakthroughs by the Ballistic Missile Defense Organization (BMDO). Miniature propulsion system work by BMDO has been expanded to include development of tiny, low mass, long life, low impulse cold gas thrusters needed to accurately control small

spacecraft sent on distant outer planet missions. Miniature optical sensors and laser inertial measurement devices allow for further reductions in spacecraft size and mass. Pluto Express software will include a high order commanding language and current prototypes use SCL (Spacecraft Command Language) demonstrated successfully on the Clementine I Mission.

MISSION DESIGN OPTIONS

The preferred flight path for a fast Pluto mission would be a direct ballistic trajectory with no planetary flybys, which approximates a straight line path between the Earth and Pluto. This results in a relatively benign radiation environment, and allows for very low cost mission operations since no gravity assist flybys and few maneuvers are entailed. However, for flight times under ten years this requires a Titan IV/Centaur or Proton class launch vehicle with at least one additional upper stage such as a typical satellite perigee raise motor. Unfortunately, these large rockets and upper stages are too expensive in today's funding environment.

In order to allow for lower cost missions on Delta or Molniya class launchers without the expense of an upper stage, there are other mission design options. Earth/Jupiter gravity assist trajectories can achieve flight times of around ten years, but require the spacecraft to be capable of surviving significantly higher radiation levels, and require a much larger onboard propulsion system. Another drawback with these trajectories is the amount of effort needed to ensure that the probability of an Earth impact during the Earth flyby is acceptably low. A straight Jupiter Gravity Assist (JGA) trajectory is available for Delta and Molniya class launchers in 2003 and 2004. This option offers simpler mission design and mission operations, but an additional upper stage and its attendant cost is required.

There is an attractive option for a Venus/Venus/Jupiter Gravity Assist (VJVJGA) trajectory which avoids an Earth flyby and can be launched on a Delta or Molniya class vehicle without an upper stage, with a flight time of about 11.8 years, launching in March 2001. There is a backup Venus/Venus/Jupiter Gravity Assist (VVJGA) trajectory available in July 2002. These options require a fairly large chemical bipropulsion module, but that results in only a modest hardware cost increase over the small monoprop system which would be required for TCM's for any Pluto mission option. Increased operations cost to

support the more complex VVVJGA mission, however, tend to offset the savings from eliminating the upper stage that would be required for the 2003/2004 JGA trajectory.

Solar Electric Propulsion (SEP) also provides attractive options for getting to Pluto in about ten years on a Solar Electric Venus Gravity Assist (SEVGA) trajectory with a Delta or Molniya class vehicle, especially after the year 2006 when Jupiter will not again be available for the lower cost gravity assist trajectories until 2013. There are also at least two SEP launch opportunities, in 2002 and 2004, for Solar Electric Venus/Venus/Jupiter Gravity Assist (SEVVJGA) trajectories, which can be performed with a much smaller and cheaper SEP Module than that for the SEVGA mission; however, this option still appears to be more costly than the VVVJGA, VVJGA, or JGA options. SEP can be used to provide thrust out to about 2 AU, after which it is discarded.

SCIENCE OBJECTIVES AND SCIENCECRAFT APPROACH

Pluto is the largest of a class of primordial bodies at the edge of our Solar System which have comet-like properties and remain relatively unmodified by warming from the Sun. Pluto is thought to be compositionally similar to Triton, the largest moon of Neptune, which was reconnoitered by Voyager 2. These two bodies may also be similar to Charon at 10 to 20 AU and the recently discovered Kuiper belt objects out at 40 AU and beyond. All of these objects probably hold important clues to the origin of comets and the evolution of the solar system. Pluto has a large moon, Charon, which has properties very different from Pluto, and this bizarre double body system may have resulted from a catastrophic planetary collision (1).

At the present time, Pluto has just passed perihelion at 30 AU and is now moving farther away from the Sun on its way out to 50 AU. Stellar occultation observations have shown that Pluto currently has a temporary atmosphere now that it has been warmed by the Sun during this very brief "summer" in its 248 year orbit. It is anticipated that these gasses will freeze out onto the planet's surface sometime over the next 2-3 decades. It is highly desirable to observe this atmosphere with UV and radio occultation experiments before it disappears, and to observe surface features and chemical makeup that may be obscured if and when the atmosphere collapses. NASA's Pluto Science Working Group has

defined a minimum set of measurements to be taken in order to map the surfaces and determine the chemical composition of Pluto and Charon, and also to measure the structure and composition of Pluto's atmosphere (2).

Meeting the science objectives at Pluto and its moon Charon calls for multi-spectral imaging and spectroscopy in visible, infrared (IR), and ultraviolet (UV) wavelengths. Technology developments are well underway to enable a highly integrated science package that delivers Voyager-class performance for a mass of under 7 kg and a power of less than 6 watts. Resolution for visible imaging is planned to be about 1 km at a distance of 100,000 km, before closest approach when the spacecraft can observe nearly the whole lighted hemisphere. Closest approach is planned at 15,000 km with a flyby velocity of around 15 km/sec.

After the Pluto encounter and data playback have been completed, it is intended that the flight system can be targeted to perform an extended-mission flyby encounter of one or more Kuiper Belt objects on its way out into interstellar space. The instrumentation planned for Pluto would also be ideal for investigation of these recently discovered mysterious objects for clues to their origin and significance to comet formation and Solar System evolution.

A new implementation approach is being used for Pluto Express whereby the Science team and Mission Operations team will be integrated with the spacecraft development team very early in the design phase. This is to ensure that the spacecraft will be optimized around the science measurements to be taken, and that the flight system will be designed to be more easily operable during the mission. Con

ARCHITECTURAL APPROACH:	Sciencecraft	Traditional AO	JIT	Modular	Redundant	Single String
IMPLEMENTATION APPROACH:	Integ. Prod. Team	Co-Location	Paperless	Traditional	Fire & Ice	Inter-program buys
LAUNCH VEHICLE:	Proton	Molniya	Delta	2 L/V's	1 L/V	
UPPER STAGE(S):	PAM-D	PAM-D/STAR 30	STAR 63/37/27	none		
TRAJECTORY TYPE:	Direct	VVVJGA	JGA	3+ΔVEJGA	SEVGA	SEEGA
LAUNCH & ARRIVAL DATES:	varies with trajectory type					
RADIATION ISSUES:	Low Radiation	High Radiation	Rad Hard Parts	Ta Shielding		
SCIENCE SCOPE:	1A Science	Grav. Assist Sci.	Cruise Sci.	Probes	Asteroid	Kuiper Object(s)
	Long Exposure Imaging (1A)		Spin Scan Imaging		Imaging Resolution	
MISSION OPS APPROACH:	Beacon Cruise	Minimum Passes	Rip van Winkle	Flyby Automation		
S/C CONFIGURATION:	Non-Stackable	Stackable for 2 or more S/C on 1 L/V				
POWER SOURCE:	Cassini-based RTG	Advanced RPS	Solar	Powerstick	Dvmt. Schedule	
TELECOM ARCHITECTURE:	Ka	X	LG/MGA ?	Optical	Ground Infrastructure	
DATA RATE OPTIONS:	HGA Size & Mass	Telecom Power	Data Compression			
ELECTRONICS TECHNOLOGY:	MCM μ-Electronics	Stacked MCM's	MIMIC's	Currently Available Technology		
ATTITUDE CONTROL:	3-Axis Stabilized	Spin Stabilized	Pointing Capability	Slew Capability		
	Body Pointed Sci.	Scan Platform				
PROPULSION:	Hydrazine	Cold Gas	Tridyne	SEP	Modular	Integral to S/C
THERMAL DESIGN:	Room Temp.	Cold	RHU's	"Thermos"		

Table 1: Pluto Express 17-Dimensional Trade Space

versely, Science and Mission Operations team members will have greater visibility into spacecraft engineering issues and be more willing to moderate and tailor their requirements in order to achieve a lower cost total system design. The science package is to be an integral part of the spacecraft, and they may share common elements rather than be stand-alone modules. This approach was conceived by David Rogers, Pat Beauchamp, Larry Soderblom, and Greg Vane in an effort to increase mission performance and decrease cost (3). The resulting flight system is called a "sciencecraft" rather than a spacecraft.

MISSION TRADE STUDIES

Pluto Express has been analyzing a number of options for flight system and mission architectures for implementing a fast flyby of Pluto. Table 1 shows the trade space considered for the option studies. Each of the 17 rows depicts one of the dimensions of the trade space, with the alternatives considered for that dimension. The dimensions which have the greatest impact on mission cost are the launch vehicle, the upper stage, and the power source. Trajectory type is a major driver in mission design, but the trajectory used is basically dependant on the launch vehicle and upper stage chosen. Operations cost, which can be significant in a 12 year mission, are most heavily driven by sciencecraft and mission design.

tope power source, and options with a 2 are solar powered. Options with a D utilize a solid rocket upper stage and are either direct trajectory or JGA. Options with an N have no upper stage, and options with an S utilize a SEP module for propulsion. Option 3 was an attempt to define the lowest cost mission to achieve the science objectives with a single flight system and without necessarily achieving the technology objectives. Option 4 was to examine the cheapest possible mission to Pluto that would send back any science at all. It is interesting that there was not much money to be saved by severely descopeing the science, since the baseline science objectives can be achieved by using an advanced technology integrated instrument with a modest cost compared to instruments traditionally flown on planetary missions.

Table 3 presents a qualitative evaluation of the seven basic options, with a few other derivative options. Detailed cost estimates were performed for these cases, but the actual cost numbers are not presented here because NASA and JPL have not yet arrived at any cost commitments for performing these possible missions. From the standpoint of mission cost and risk, Options 1D and 1N and their derivatives appear to be the most attractive. The Option 2 variations entail substantial operational risk due to the extremely limited energy available at Pluto -- energy that would prove insufficient for keeping the spacecraft alive during recovery from a

Option:	RPS/PAM-D /Proton	RPS/SEP/Molniya	RPS/none/ Molniya	Solar/none/ Molniya	Solar/SEP/Molniya	RTG/none/ Molniya	RTG/none/ Molniya
	1D	1S	1N	2N	2S	3	4
Number of Sciencecraft	2					1	
Type of launch vehicle	Proton	Molniya (Delta backup)		Atlas 2		Molniya	
Number of launch vehicles	2					1	
Upper stage or SEP mod'l.	PAM-D	3 eng. SEP w/ S/A	none		6 eng. SEP w/o S/A	none	
Trajectory	Direct	SEVVJGA	VVVJGA	3+ΔVEJGA	SEEGA	VVVJGA	
Power source	RPS			solar/batteries		Cassini RTG	
Stabilization	3 axis			3 axis/spin		3 axis	spin
Science pointing	Sc/C body			Scan Platform		Sc/C body	spin scan
Structure	Composite					Aluminum	
Transmitter	Ka SSPA			Ka SSPA/TWTA		X SSPA	
Computer	AFC					Cheaper	Lower capability
Propulsion	Hydz/Cold G		Biprop/C G		Monoprop Hydrazine	Hydz/Cold G	Hydz. only
Tanks	Composite					Titanium	
Temperature Control	RPS			RHU's		RTG	
Electronic Packaging	MCM stack					Black box	

Table 2: Pluto Express Basic Trade Study Options

There are several billion possible mission options that could be derived from this trade space, but for purposes of this study, the seven basic options shown in Table 2 were chosen to illuminate what were considered to be the most fruitful areas of the trade space. Options with a 1 indicate a radioiso-

major in-flight anomaly or loss of attitude control. Option 3 is somewhat less expensive, because it only has one flight system, but that also lowers the probability of mission success for a ten year mission and is therefore considered less attractive at this time.

	# of Sci/C	Total Mission Cost	Mission Risk	Sched. Flexibi- lity	Number of G.A. Flybys	Launch Vehicle Availa- bility
RPS/PAM-D/Proton (1D)	2	+	+	+	0	-
RPS/PAM-D/Molniya	2	+	+	o	1	o
RPS/PAM-D/Delta	2	o	+	o	1	+
RPS/none/Molniya (1N)	2	+	+	o	3-4	o
RPS/none/Delta	2	o	+	o	3-4	+
RPS/SEP/Molniya (1S)	2	o	+	+	1-3	o
RPS/SEP/Delta	2	-	+	+	1-3	+
Solar/none/Molniya (2N)	2	-	-	o	2	o
Solar/none/Delta	2	-	-	o	2	+
Solar/SEP/Atlas 2 (2S)	2	-	-	+	1-2	+
RTG/none/Molniya (3/4)	1	+	o	o	3-4	o
RTG/none/Delta	1	+	o	o	3-4	+

Legend: + is good
o is marginal
- is bad

Table 3: Pluto Express Trade Study Evaluation Matrix

OPTION 1N FLIGHT SYSTEM DESIGN

For a launch in the 2001/2002 time frame, Option 1N is currently considered to be the most cost effective and lowest risk means of achieving the desired science goals at Pluto. The sciencecraft flight sys-

tem for Option 1N consists of a Sciencecraft Module (comprised of both hardware and software), a Propulsion Module, and attached probes. The major hardware elements are depicted in the functional element layout shown in Figure 1. In this diagram, sciencecraft components are classified into three major groups: sensors, electronics, and motive effectors. These elements are integrated together inside of a structural and thermal enclosure. Additionally, a power source provides electrical and thermal energy to the sciencecraft system.

It is planned that many of the electronic components will be integrated into a three dimensional stack of Multi-Chip Modules (MCM's) to greatly reduce the volume, mass, and the amount of cabling required. The small size also significantly reduces the mass of any additional radiation shielding required. This MCM stack will consist of the Sciencecraft Data Subsystem (SDS) with its block redundant flight computer and solid state mass memory, and

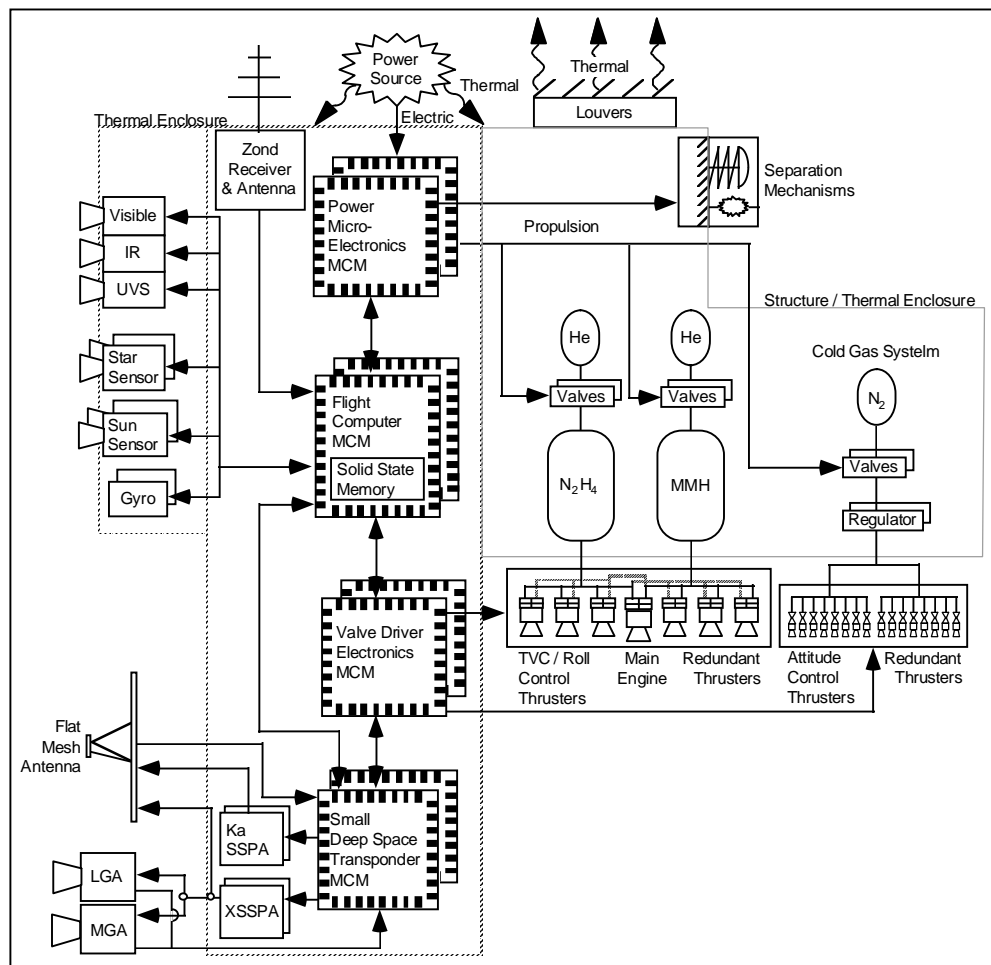


Figure 1: Pluto Express Sciencecraft Hardware Functional Element Layout

power control electronics for instruments, electronics, and pyrotechnic initiators. It is anticipated that the valve driver electronics for the propulsive thrusters and the Telecommunication Subsystem electronics will be housed in separate electronic packages to reduce interference problems with the other subsystems.

	Mass	Power
TELECOMMUNICATIONS		
Antennas	5.30 kg	
Transmitter & Receiver	8.70 kg	29.0 W
Waveguide/Switches/Misc.	6.50 kg	
POWER & PYRO		
Radioisotope Power Source	6.10 kg	
Power Micro-electronics	2.70 kg	12.0 W
ATTITUDE CONTROL		
Star Sensors	1.00 kg	1.5 W
Inertial Reference Units	0.40 kg	4.0 W
Sun Sensors	1.00 kg	0.2 W
Valve Driver Electronics	4.75 kg	2.5 W
DATA SUBSYSTEM		
Advanced Flight Computer Assy.	2.40 kg	6.0 W
MCM Stack Housing	1.00 kg	2.4 W
STRUCTURE & CABLING		
Bus Structure	2.72 kg	
HGA Support Structure	1.20 kg	
Fittings & Brackets	2.00 kg	
Cabling	5.00 kg	
THERMAL CONTROL		
MLI Blankets	1.40 kg	1.0 W
Louvers	0.80 kg	
Misc.	2.20 kg	
SCIENCE		
Multi-Spectral Instrument	5.40 kg	5.0 W
Radio Science	1.00 kg	1.0 W
Miscellaneous	0.50 kg	
Subtotal	62.07 kg	64.6 W
PROPULSION MODULE		
Tanks	28.60 kg	1.0 W
Structure	19.00 kg	
Propulsion Components	25.60 kg	
Thrusters	5.40 kg	
MLI Blankets	5.50 kg	
L/V Separation Mechanisms	1.50 kg	
Propellants	306.00 kg	
20% Contingency	90.73 kg	13.1 W
ATTACHED PROBES		
Russian Drop Zond	15.00 kg	
German Io Probe	15.00 kg	
TOTAL WET MASS	574.4 kg	78.7 W

Table 4: Sciencecraft Mass and Power

The Sciencecraft Module dry mass is estimated to be about 95 kg, including a 30% contingency. There are a number of different power modes, depending on mission phase, but the peak power usage during encounter is about 75 watts, including a 15% contingency. Mass and power estimates are summarized in Table 4.

Mechanical Design and Temperature Control

The flight system configuration, shown in Figure 2, is dominated by the Propulsion Module. A central structural core contains two helium pressurant tanks for the fuel and oxidizer, and a nitrogen tank for attitude control propellant. This structure also supports the fuel and oxidizer tanks on the outside with struts. At the bottom of the Propulsion Module is the main engine and attitude control thrusters. The Propulsion Module structure would be used to mount Pluto and/or Io probes and their radio relay hardware.

Mounted to the top of the Propulsion Module is a modular bus structure comprised of four trapezoidal panels fabricated from a graphic composite material. One of the panels is used to mount the science package on the exterior. Another panel is used to support telecommunication components on the interior and temperature control louvers on the exterior. The interior of the other two panels support gyros, valve driver electronics, and the integrated MCM microelectronics package, while the exterior surface of one of these panels supports the star sensors. Mounted to the top of the bus is a 1.5 meter diameter para

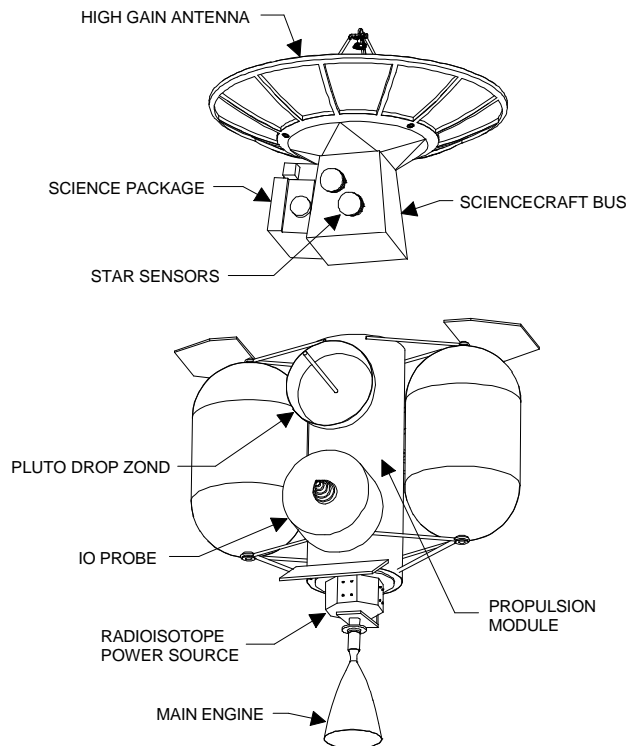


Figure 2: Pluto Express Sciencecraft

bolic High Gain Antenna (HGA) which is used for communications to a distance of 30 Astronomical Units (1 AU = 150 million km) from the Earth and beyond. This advanced composite ultralight HGA is also used as a sunshade for the flight system during operations between 0.6 AU and 1 AU.

If a 100 watt electric Radioisotope Power Source (RPS) is used, it will be mounted to the Propulsion Module so that some of its 500 watts of thermal output can be used to warm temperature-critical elements such as propulsion components, the propellant tanks, and electronics in the bus. Radiated heat from the RPS is directed and controlled by Multi-Layer Insulation (MLI) blankets and louvers to create several thermal zones. Some Radioisotope Heater Units (RHU's) would also be needed for temperature control. Analysis indicates that this design can maintain temperatures within specification with little or no use of electrical heaters, over a range of 0.6 to 30 AU from the sun. This represents a factor of 3,700 difference in solar illumination.

Sciencecraft Data Subsystem

The sciencecraft avionics consist of a number of standardized MCM's which will be integrated together in a three dimensional stack as shown in Figure 3. This modular stacking greatly decreases the

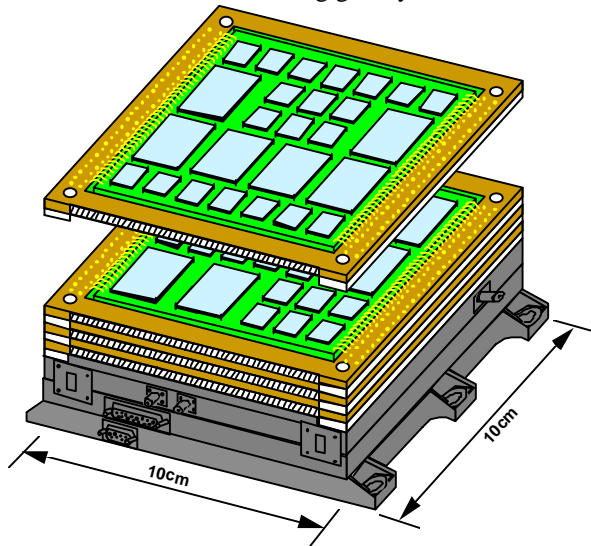


Figure 3: Integrated Microelectronics MCM Stack volume and mass of electronics and reduces the mass of cabling and connectors. Significant progress has been made in this development (4), and prototype MCM's for the Advanced Flight Computer (AFC) have already been produced. The AFC is

currently being readied for flight on the TRW *Lewis* spacecraft and the New Millennium Deep Space 1 (DS-1) mission. Signals are carried between the MCM's through terminals at their perimeter. It is important to standardize the locations of the power and data terminals in order to maintain modularity and architectural flexibility in this new packaging technology.

The Sciencecraft Data Subsystem (SDS) will have two identical processors, one for engineering and the other for science. There will also be two redundant blocks of 2 Gbit DRAM "solid state recorder" for storing science and engineering data. The two computers and their large data storage memories are cross strapped together so that one processor can take on all functions in the event of a failure and access both memory blocks.

Attitude Control

Attitude control pointing capability is estimated to be 2 mrad with a rate control of 10 μ rad/sec or better (3 sigma). This is driven by visible imaging and IR mapping spectrometry requirements to achieve 1 km resolution at 100,000 km from Pluto. The primary reference for pointing is a star sensor which is used to image whatever star field lies in its view area. Centroids of the stars are calculated, and the pattern is compared to a star map stored onboard to calculate the orientation of the sciencecraft. In order to achieve the desired pointing accuracy, this process will take place about every 400 msec (2.5 Hz).

During Trajectory Correction Maneuvers (TCM's), delta V burns, or during some emergency scenarios, the attitude reference is taken over by an Inertial Reference Unit with a bias instability of about 1° per hour (3 sigma). Sun sensors are included on the sciencecraft to help with initial attitude acquisition following launch, and for certain emergency recovery scenarios.

Telecommunications

Pluto Express plans to utilize the advanced technology Small Deep Space Transponder (SDST) for communications with the Earth. This unit employs Monolithic Microwave Integrated Circuits (MMIC's) implemented on MCM's at very small mass and volume. The output of the SDST will feed GaAs PHEMT (Pseudomorphic High Electron Mobility Transistor) Solid State Power Amplifiers (SSPA's).

Uplink is X-band at 7.1 GHz, and downlink is planned to have both X-band and Ka-band capability.

A 1.5 m diameter High Gain Antenna (HGA) provides a data rate of between 150 and 450 bits/sec, depending on the DSN ground antenna station configuration used. Benefits of the increased data rates from possibly using a larger HGA are being evaluated and will be traded off against the mass increase which would result. A Low Gain Antenna (LGA) and a single-axis steerable Medium Gain Antenna (MGA) are included to allow communications early in the mission in situations where the HGA is not pointed directly at Earth. This is needed for initial acquisition after launch, for cruise inside 1 AU, and for certain emergency scenarios. After the flight system passes the orbit of Mars, the LGA will no longer be able to provide a data link, and the operations must depend on the HGA and MGA.

Power

A Radioisotope Power Source (RPS) using heat from radioactive decay to generate electricity is the most robust technology available today for providing reliable power at edge of the solar system and out into interstellar space. Radioisotope generator technology used for *Galileo*, *Ulysses*, and *Cassini* is usable for the Option 1N Pluto mission at about a 7% conversion efficiency. More advanced converter technologies are being developed to increase the efficiency of these devices up to about 20%, and enabling the Pluto 1N sciencecraft option to fly a much lighter power source with about 25 times less radioisotope material than *Cassini*, in part due to lower power usage.

Propulsion

To achieve fine pointing control of a low mass flight system with very small moments of inertia, it is necessary to have extremely low impulse thrusters so that the vehicle is not overly torqued when they fire. Long life dry nitrogen cold gas thrusters that provide a force of only 0.0045 N are currently being developed for the Pluto mission. The total amount of gas required for providing attitude control over the ten year mission is less than 1 kg.

For Trajectory Correction Maneuvers (TCM's) and large delta V burns, a **500 N** bipropellant main engine will be used. Separate high pressure helium tanks pressurize the hydrazine and nitrogen tetrox-

ide tanks that feed the main engine and the twelve 10 N Thrust Vector Control (TVC) thrusters.

SOFTWARE

The two most important design considerations for Pluto Express software are low cost development and low cost operations. Low cost development is to be achieved through use of a testbed early in the design process and by leveraging reusable software and Commercial Off The Shelf (COTS) products. To achieve low cost operations, Artificial Intelligence (AI) based methods are being developed to create a highly robust and autonomous flight system. Similar flight and ground software architectures will allow easy migration of functions from the ground to the flight system. An emphasis on concurrent engineering of flight and ground systems early in the design process will produce a highly operable sciencecraft to further lower life cycle cost.

Software development for Pluto Express has already begun through evolutionary, rapid prototyping activities in a testbed environment. Flight software prototypes running on a target processor interface with subsystem simulations through flight-like message passing software. As breadboard subsystem hardware becomes available, it will be integrated into the end-to-end system. New capabilities will be continuously integrated to improve the overall fidelity and to create a working end-to-end prototype before assembly of the flight version of the sciencecraft begins.

A significant amount of Pluto Express flight software will be developed and uplinked after launch. It is highly unlikely that the code running in the sciencecraft during encounter in 2013 will be code designed pre-launch. To provide for this needed flexibility, the flight data system is designed for robustness including significant margins in program memory, MIPS, and bulk data storage. In addition, the flight software architecture is being designed to accommodate years of post launch changes.

ATTACHED PROBES

Discussions have been held with the Space Research Institute (IKI) in Russia about the possibility of having the Pluto sciencecraft deliver a Russian probe, called a "Drop Zond," to Pluto. The flight system would be initially put on a course to impact Pluto, and then about 30 days out from encounter,

the Drop Zond would be oriented, spun up for stabilization, and released to fly on its own. Then the main sciencecraft would perform a deflection maneuver and be retargeted to miss Pluto and execute its nominal flyby encounter.

As the Drop Zond nears Pluto, the main sciencecraft would receive encounter data transmitted by the Zond and store it on board the SDS DRAM. The Zond would perform in-situ measurements of Pluto's atmosphere and take images of the planet as it closed in. Images would be received right up until the point of probe destruction or loss of signal, similar to the Ranger moon missions. After the Pluto encounter is completed, the Zond data would be played back for transmission to Earth.

MISSION OPERATIONS AND AUTONOMY

In order to greatly reduce the cost of mission operations during the long flight to Pluto, a concept has been developed called Beacon Cruise (5). It is planned that the HGA will continuously be pointed at the Earth during cruise with the receiver operating and the transmitter broadcasting suppressed carrier with one of four possible tones. Each tone represents the urgency at which the sciencecraft is requesting ground action to schedule a telemetry/command track. The four tones/four levels of urgency are:

RED	Track as soon as possible
YELLOW	Track within a certain time
ORANGE	Track when convenient
GREEN	No tracking required

This carrier will be receivable by smaller ground antennas and simpler ground stations than are normally associated with deep space missions, so that much of the sciencecraft health monitoring can be performed on a loosely scheduled basis by colleges or other non-Deep Space Network (DSN) facilities. If the beacon indicating a problem is received, then the sciencecraft will be tracked more intensively by the DSN, and an emergency response team will be assembled to resolve the problem.

In order for beacon monitor operations to become viable, the spacecraft must be robust enough to allow it to go long periods without assistance from the ground. Onboard autonomy technologies will allow the spacecraft to react adaptively to onboard events and to summarize effectively any behaviors that must be communicated to ground operators. These

concise summaries of engineering telemetry will provide ground personnel with a complete understanding of onboard events leading up to an interesting event or anomaly.

Beacon monitor operations will result in a much smaller ground team and less DSN tracking during the mission cruise phase. The operations staff will decrease gradually during the cruise phase and will remain very small until a few months before the Pluto/Charon encounters.

SUMMARY

Advanced technologies are enabling a new class of highly capable low mass sciencecraft capable of opening up the solar system to low cost exploration from distances of very near the Sun, all the way out into interstellar space. New developments in flight system autonomy and Mission Operations are expected to drastically reduce the workforce and cost required to track and operate these vehicles. The Pluto program hopes to capitalize on these opportunities to visit the last unexplored planet in our Solar System and possibly explore Kuiper Belt objects on its way out into interstellar space.

ACKNOWLEDGMENTS

Many people on the Pluto Express Team contributed to the work described herein and provided assistance to this publication, including Doug Abraham, Leon Alkalai, Steve Brewster, Greg Carr, Savio Chau, Shawn Goodman, Volodya Gotlib, Paul Henry, Marty Herman, Glen Kissel, Linda Lievense, Slava Linkin, Ed Mastal, Robert Miyake, Annette Nasif, Fritz Neubauer, Candida Nunez, Oleg Papkov, Leon Strand, and Mark Underwood.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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